Making shipping greener: ORC modelling in challenging environments

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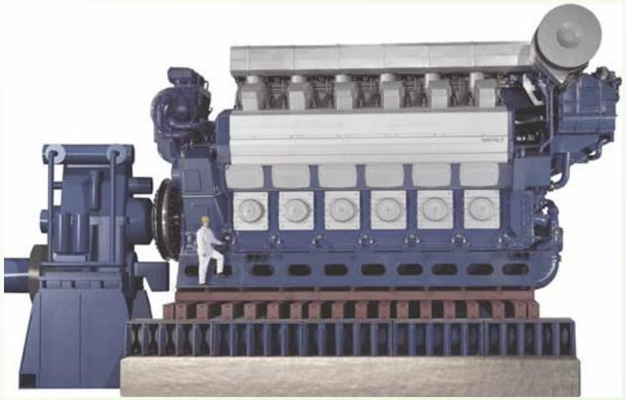
Motivation

- Shipping CO_2 emissions / Energy Efficiency Design Index (EEDI).
- Lack of comparison between thermodynamic waste heat recovery systems (WHRS) under shipping scenarios.
- How ship's operational conditions affect the performance of the thermodynamic WHRS?

(1)

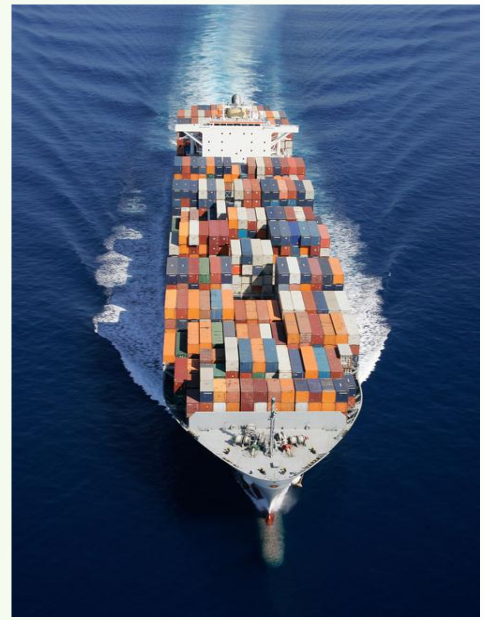
Propulsive Energy Map

Hull Friction
Wave Generation



(4)

≈ 50%



Other losses

≈ 15%

(3)

Low/Medium waste heat

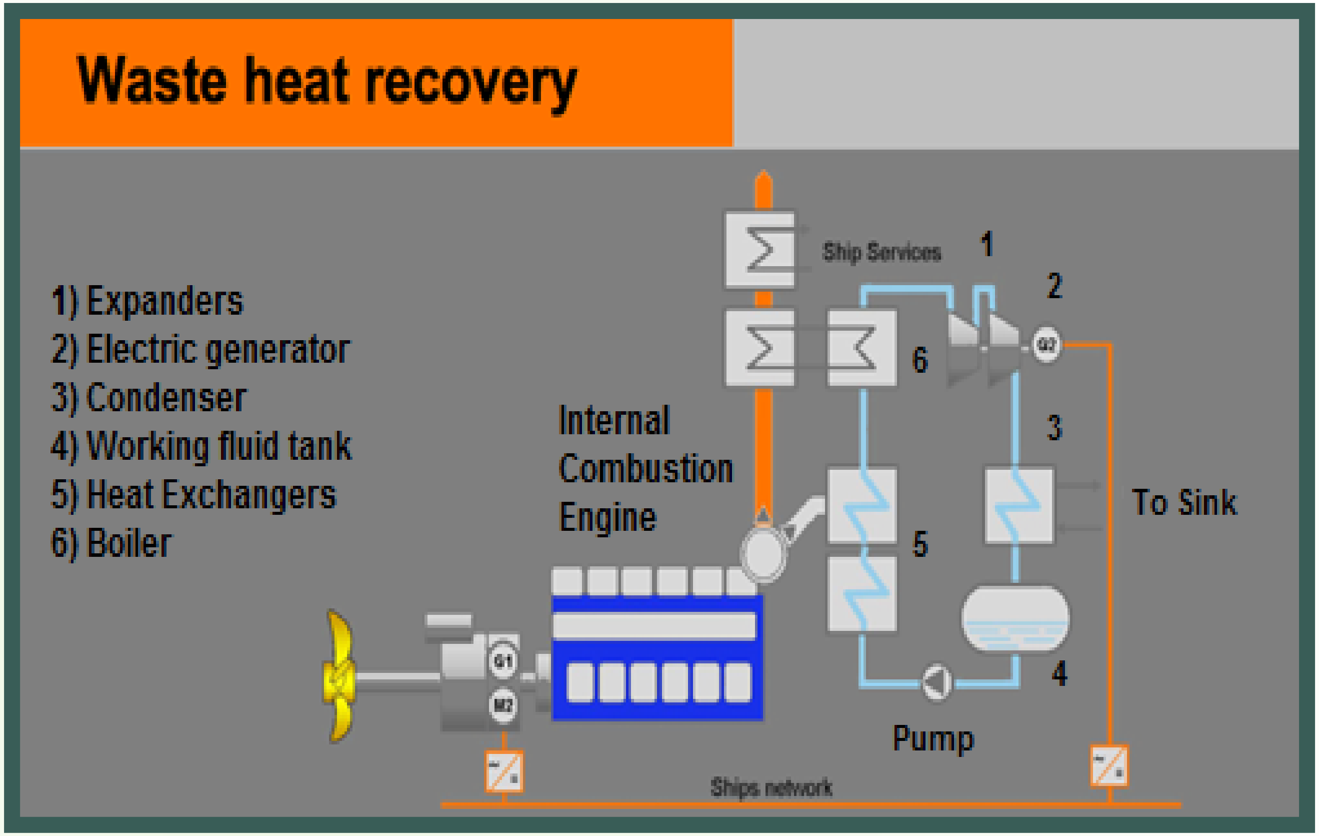
(Between
30 – 650ºC)

- Exhaust gas
- Scavenge air
- Cooling Water
- Other

(5)

Only a maximum of 35% of the combustion energy ends as propulsion power (2)

Waste Heat Recovery Systems



(6)

- Power Increase
- Fuel Consumption reduction
- CO_2 reduction

Ship's WHRS characteristics

UCL

Performance

Adaptable

Compact

Safe

Light

(7)

Objectives

Water Rankine Cycle

VS

Organic Rankine Cycle

(8)

Compare under ship's operating conditions:

- Thermal Efficiency
- Power Output
  - Fuel Consumption
  - CO_2 Emission reduction

Ship's WHRS

	Rankine Cycle	Organic Rankine Cycle
Manufacturers	MAN and Wärtsilä	OPCON
Used in	Exhaust Gas System	Boiler System
Comments	• Assisted with a gas turbine to cover larger scope of engine loadings • Benefits of up to 12% of the power output. (9)	• Limited to steam not used (Low quality heat). • Achieves a 5% fuel consumption reduction. (10)

Few papers talk about them in a ship scenario, but they have not been yet compared under variable conditions.

	Rankine Cycle	Organic Rankine Cycle
Authors	(Hatchman 1991) (11), (Theotokatos & Livanos 2012) (12)	(Ghirardo et al. 2011) (13), (Larsen et al. 2013) (14)

Methodology

- To find the WHRS optimum points the high pressure was changed up to the Critical pressure.

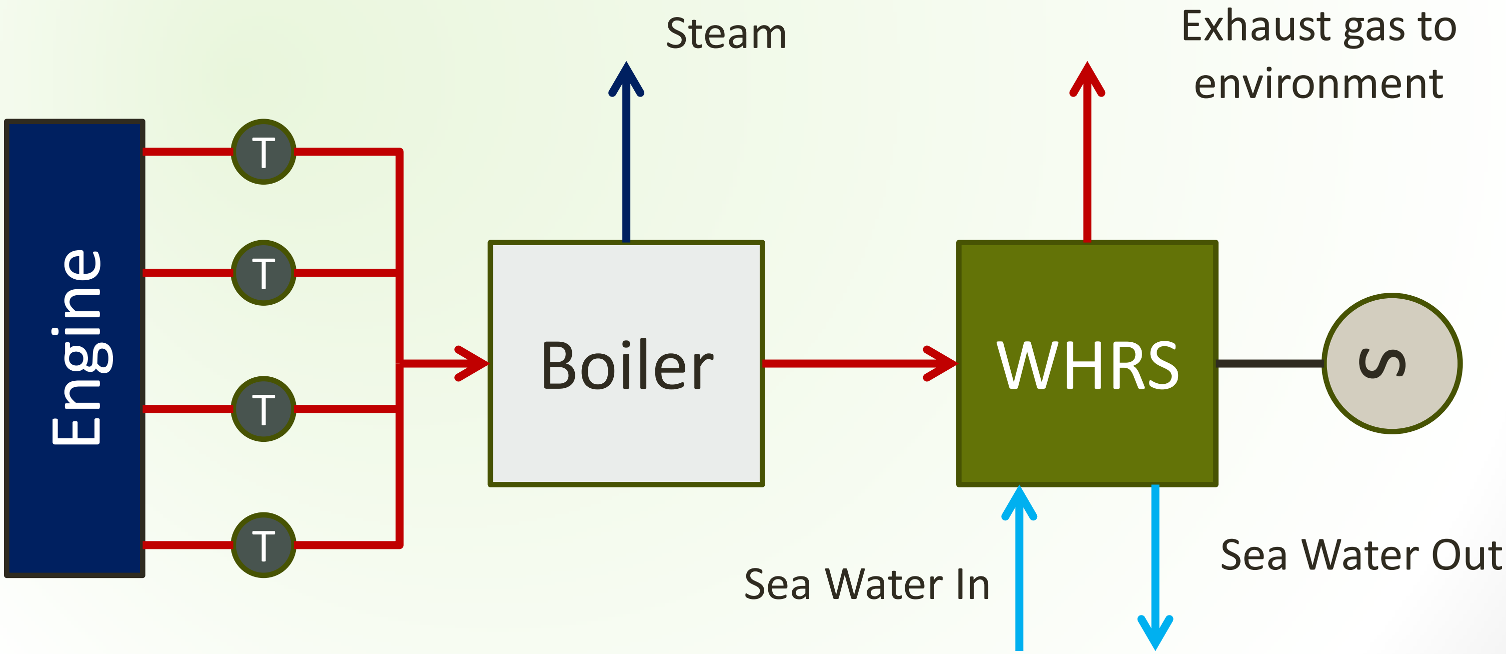
Assumptions

- The exhaust gas is treated as air, with its heat capacity as the average temperature between the exhaust inlet and outlet.
- The electrical efficiency of the generator and pumps are the same and stay constant.
- No pressure changes except for the expander and pump.
- No heat losses in the working fluid circuit except the ones set for the heat exchangers.
- No leakages.
- Steady-state operation.
- The equipment is capable of handling different mass flow rates and pressures.

The Engine

MAN slow speed Diesel Model 14K98ME7.1-TII with four turbos (15).

- Engine's Fuel Consumption per hour @85% MCR:
  12.70 Metric tons of Marine Diesel Oil
- Power output @85% MCR: 74,137 kW
- Steam production @85% MCR: 15,240 kg/h



T - Turbos

The Engine

The performances are at the maximum net power output obtained in each engine loading scenario. Some points are shown in the following table (15).

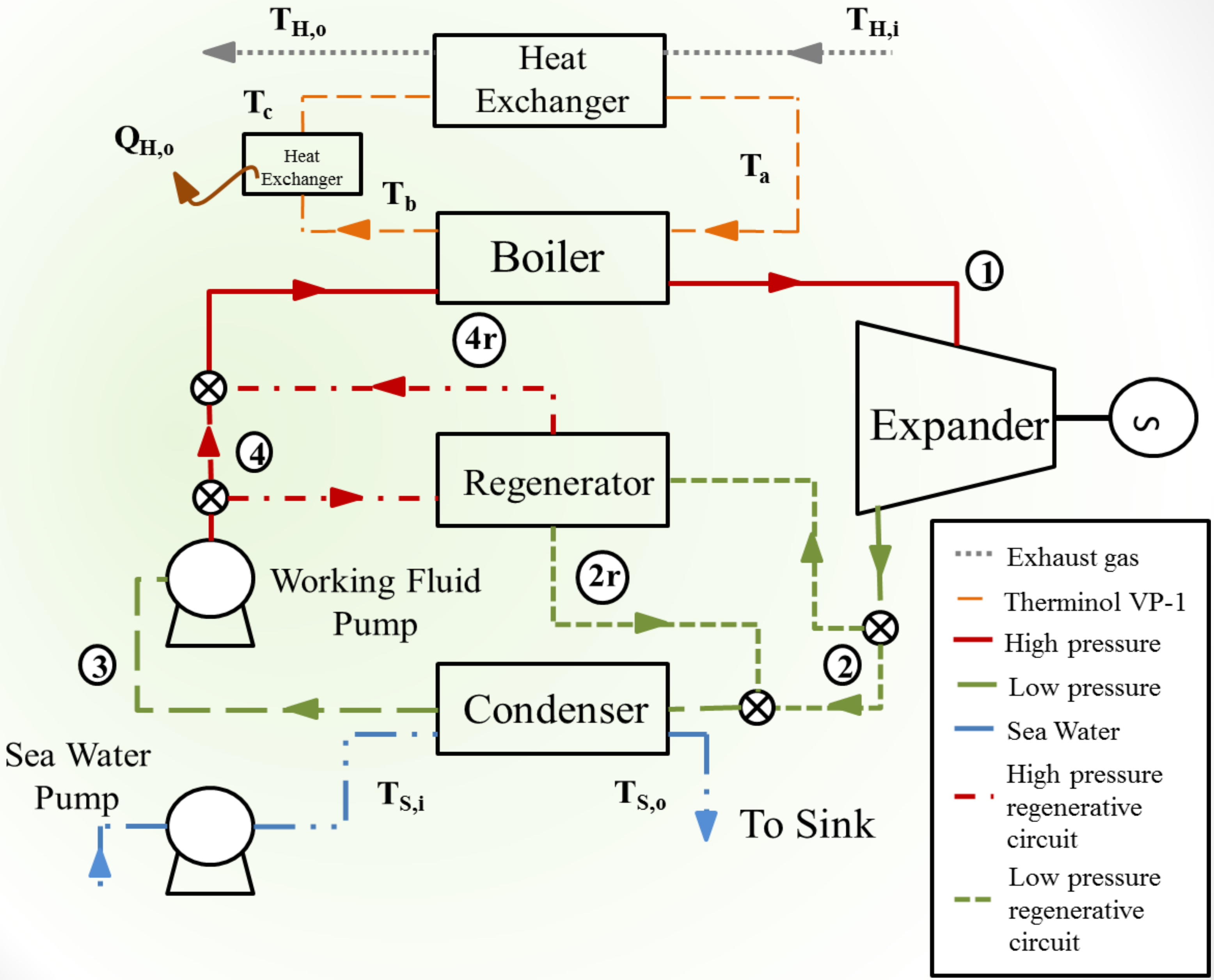
Engine Load (% MCR)	Power (kW)	Exhaust mass flow rate (kg/h)	Specific Fuel Oil Consumption (g/kWh)	Temperature (K)	Specific heat (kJ/kg-K)
100	87,200	744,300	175.5	557.15	1.028
85	74,137	687,300	171.3	518.15	1.025
75	65,415	647,700	168.6	491.15	1.022
50	43,610	465,300	169.5	501.15	1.023
40	34,888	385,200	171.7	516.15	1.025
30	26,166	352,200	174.1	482.15	1.022
25	21,805	297,500	176.1	488.15	1.022
15	13,083	212,000	184.1	468.15	1.020

Generator

- In order to understand the magnitude of the fuel savings it was used for this comparison a Wärtsilä 16V32 genset with the following characteristics:
  - Electrical Power: 8430 kW_e (with an efficiency of around 96%)
  - Fuel consumption: 176 g/kWh.
  - Fuel used: Marine Diesel Oil.
    - Cost per metric ton: €697 (26/09/2013) (17)

(16)

WHRS Layout



$T_{H,o}$
$T_{H,i}$
Heat Exchanger
T_c
$Q_{H,o}$
Heat Exchanger
T_a
T_b
Boiler
1
4r
Expander
S
4
Regenerator
Working Fluid Pump
2r
3
2
Condenser
Sea Water Pump
$T_{S,i}$
$T_{S,o}$
To Sink
Exhaust gas
Therminol VP-1
High pressure
Low pressure
Sea Water
High pressure regenerative circuit
Low pressure regenerative circuit

Working Fluids

Working Fluids	T_c * (K)	P_c * (MPa)	Notes from the fluid +
Water	647.10	22.06	
Benzene	562.02	4.91	Highly flammable, irritating.
Toluene	591.75	4.13	Extremely flammable, irritating.
Heptane	540.13	2.74	Highly flammable, irritating, harmful to aquatic life.
Hexamethyldisiloxane (MM)	518.70	1.94	Highly flammable, irritating, harmful to aquatic life.

These fluids were selected because of their Low Global warming and Ozone depleting coefficient.

* (18)
+ Comments are written as found in the Annex VI Regulation 1272/2008 of the Institute for Health for Consumer Protection (19).

Results: Variable Engine Loading

Maximum electric power output

- Highly dependant in the heat availability.

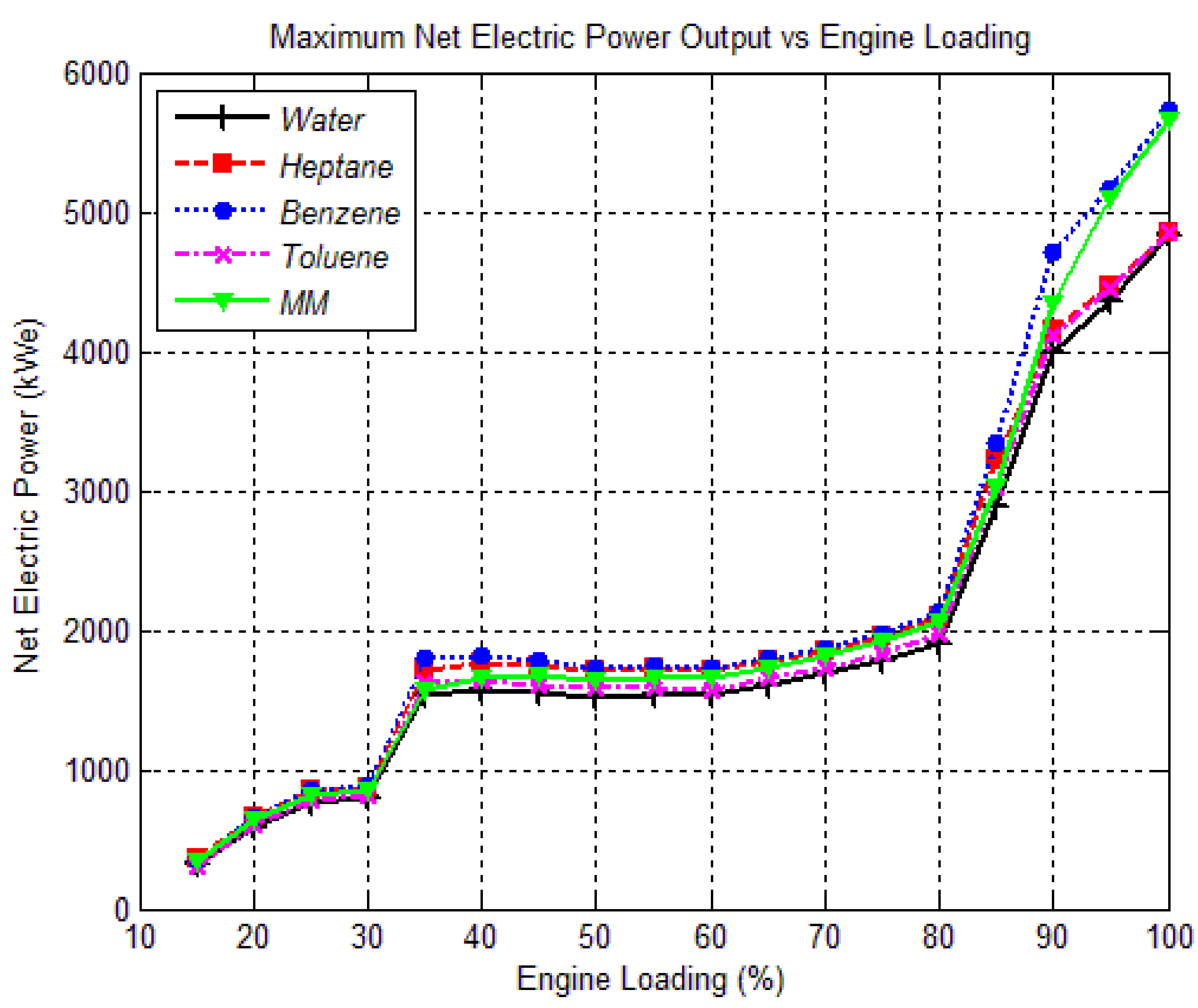
Higher

Benzene
5.7 MWe

Lower

Water
4.8 MWe

18.4% lower



Results: Variable Engine Loading

Thermal efficiency

- Highly dependant in the heat quality.

<u>Higher</u>

MM

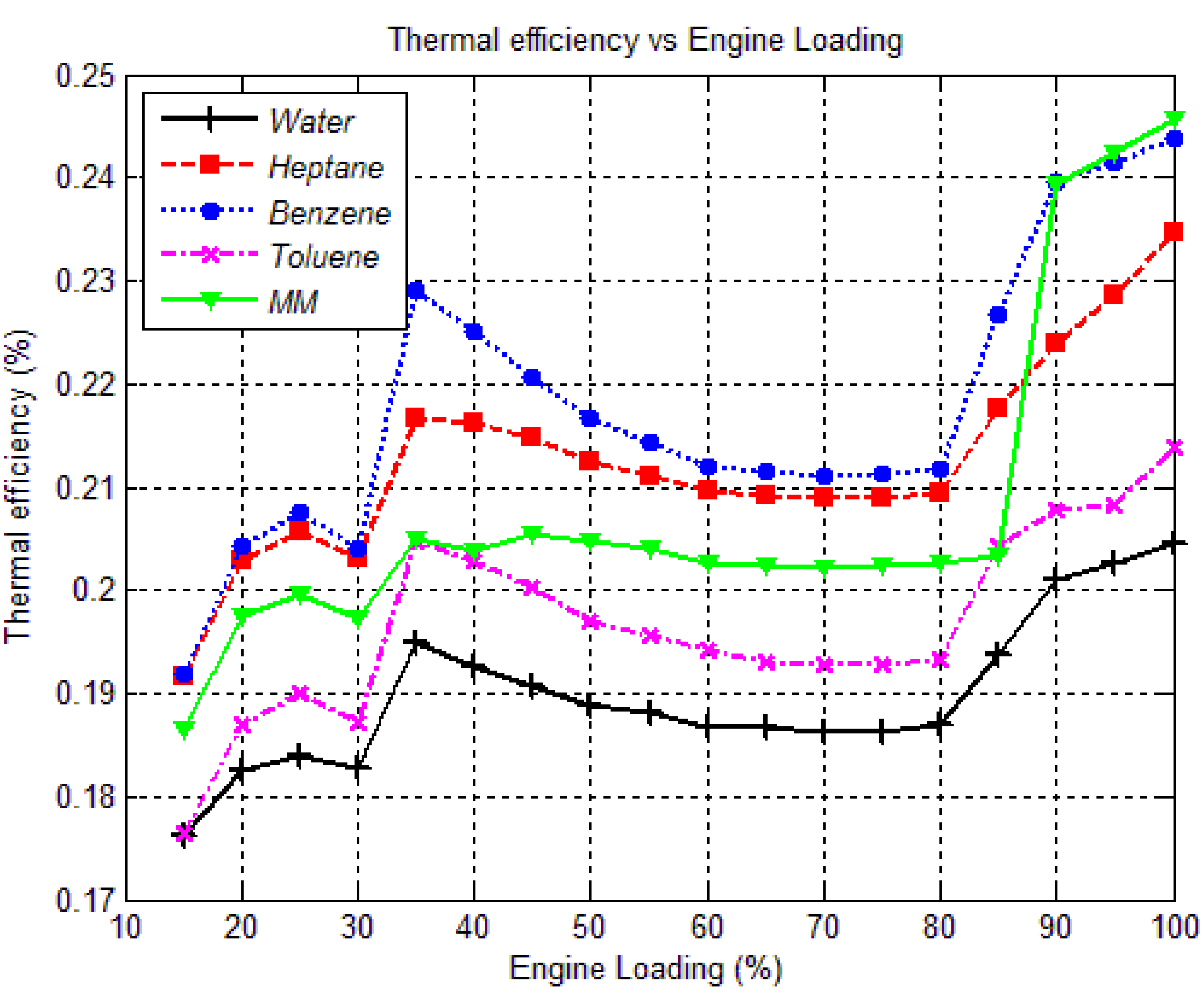
24.5%

16.3% higher

<u>Lower</u>

Water

20.5%



Results: Variable Engine Loading

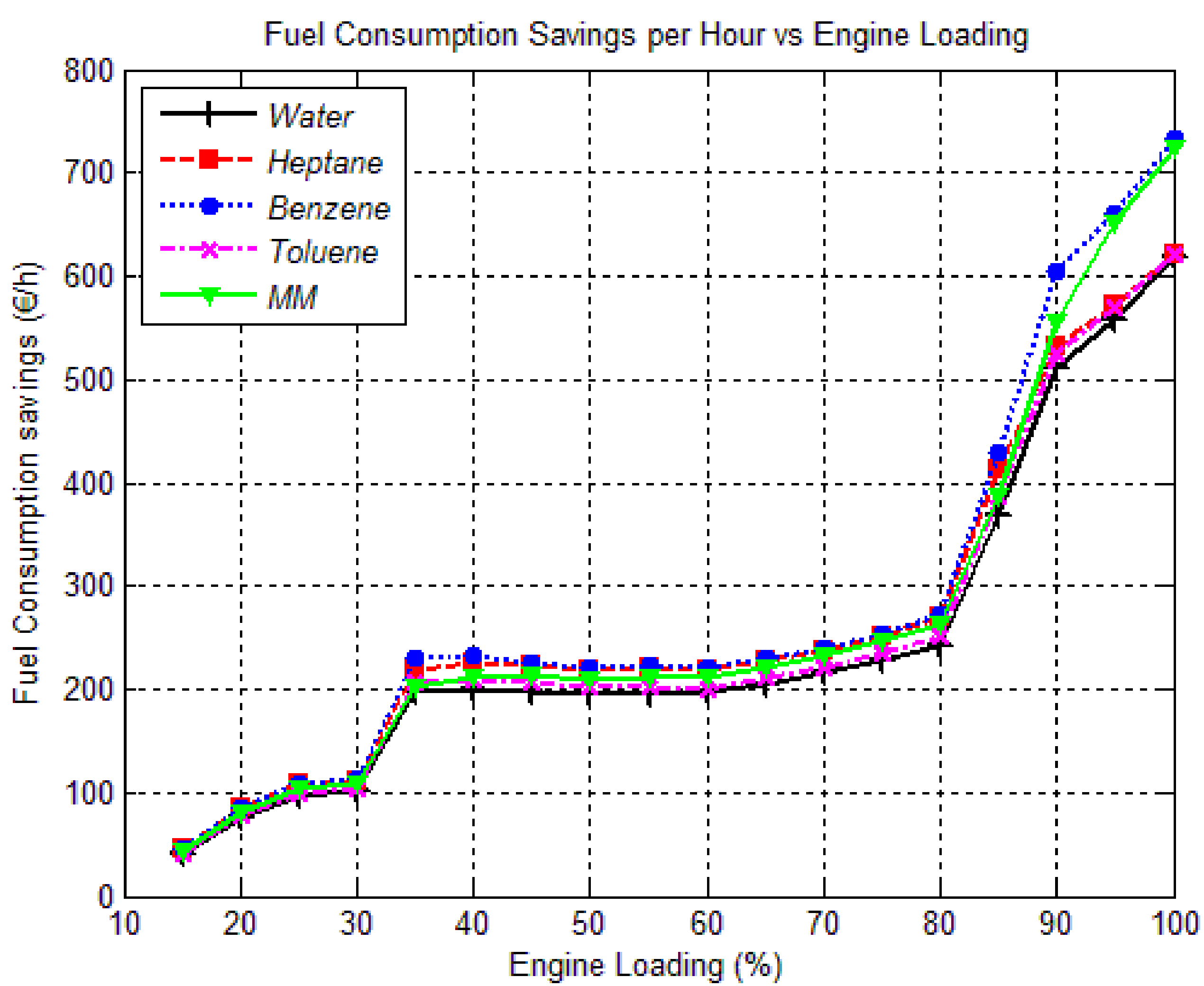
Fuel savings (assuming mechanical power)

- Highly dependant in the heat quality.

Higher
Benzene
€732/h

An overall improvement of **15.6%** from RC

Lower
Water
€618/h



Operational hours

- A container ship works around 6,480 hours per year.
- The engine loading in a year is as follows (9):

Engine Load (% MCR)	Percentage of time (%)	Total hours in a year (h)
100	1	65
90	5	324
85	5	324
80	**20**	**1296**
75	**15**	**972**
70	**15**	**972**
60	10	648
50	10	648
35	13	842
15	6	389

Design point (rows 80, 75, 70)

Points not appearing in the table had insignificant operating time.

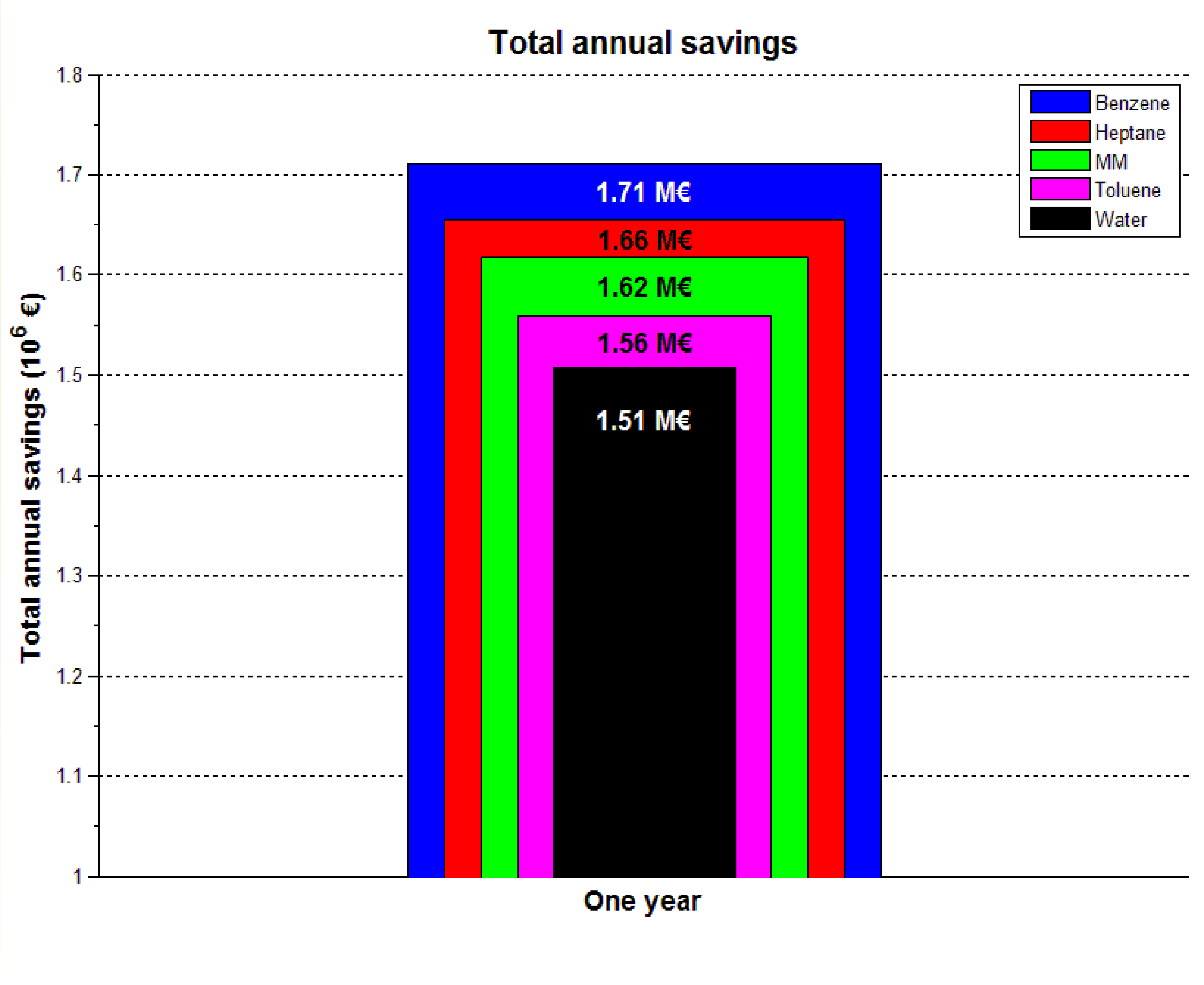
Results: Variable Engine Loading

Fuel savings in a year

Higher
Benzene
€1.71 million

In 20 year of operations the ORC will save around **€4 million** more than RC

Lower
Water
€1.51 million



Results: Variable Engine Loading

CO_2 reductions in a year

Higher

Benzene

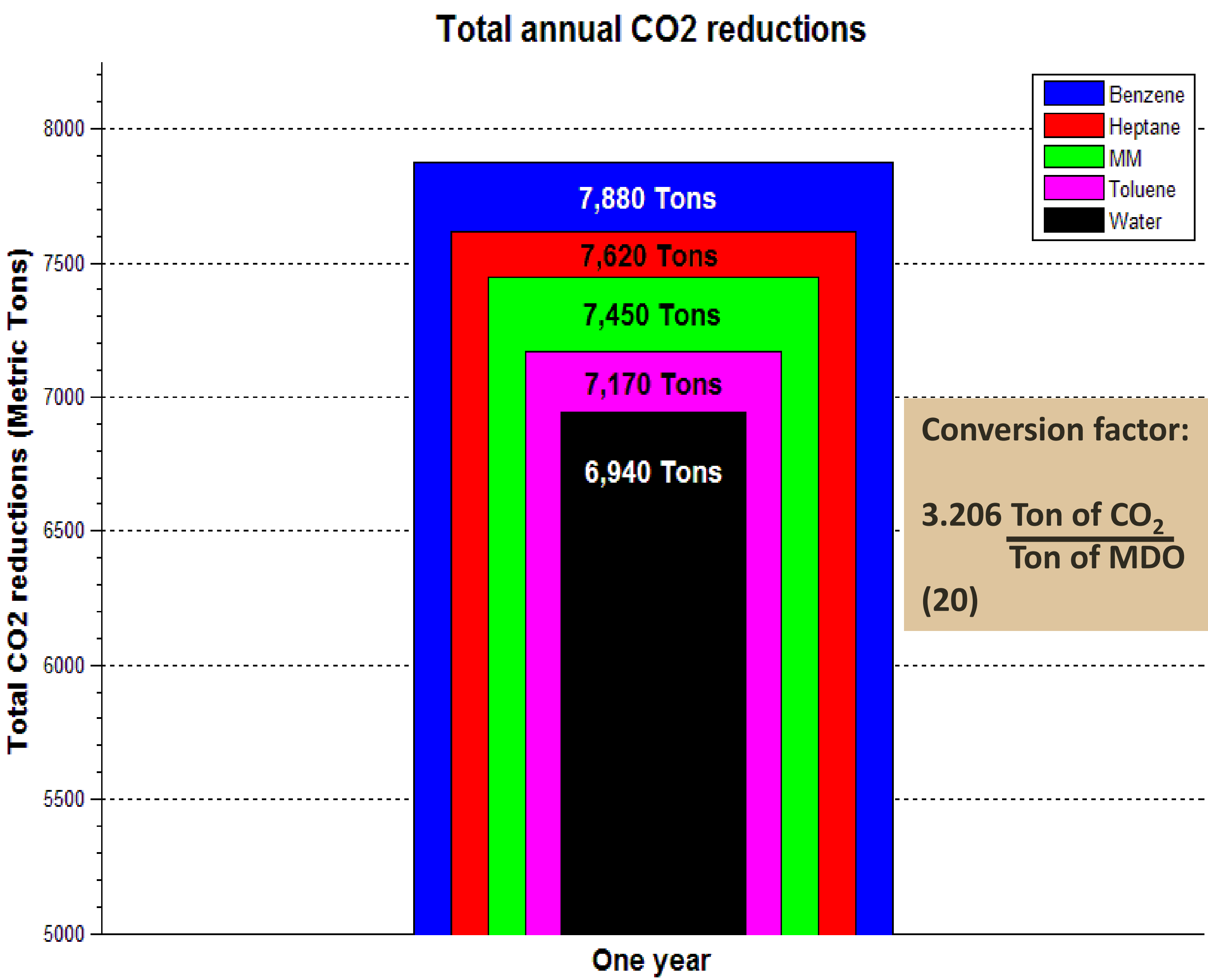
7,880 CO_2 Tons

In 20 year of operations the ORC will save around **$18x10^3$ CO_2 tons** more than RC

Lower

Water

6,940 CO_2 Tons



Conversion factor:

3.206 Ton of CO_2 / Ton of MDO (20)

Conclusions

The different WHRS are sensible to the heat quality and availability, but also their benefit is affected by the engine's own performance.

ORC WHRS outperforms the RC by:

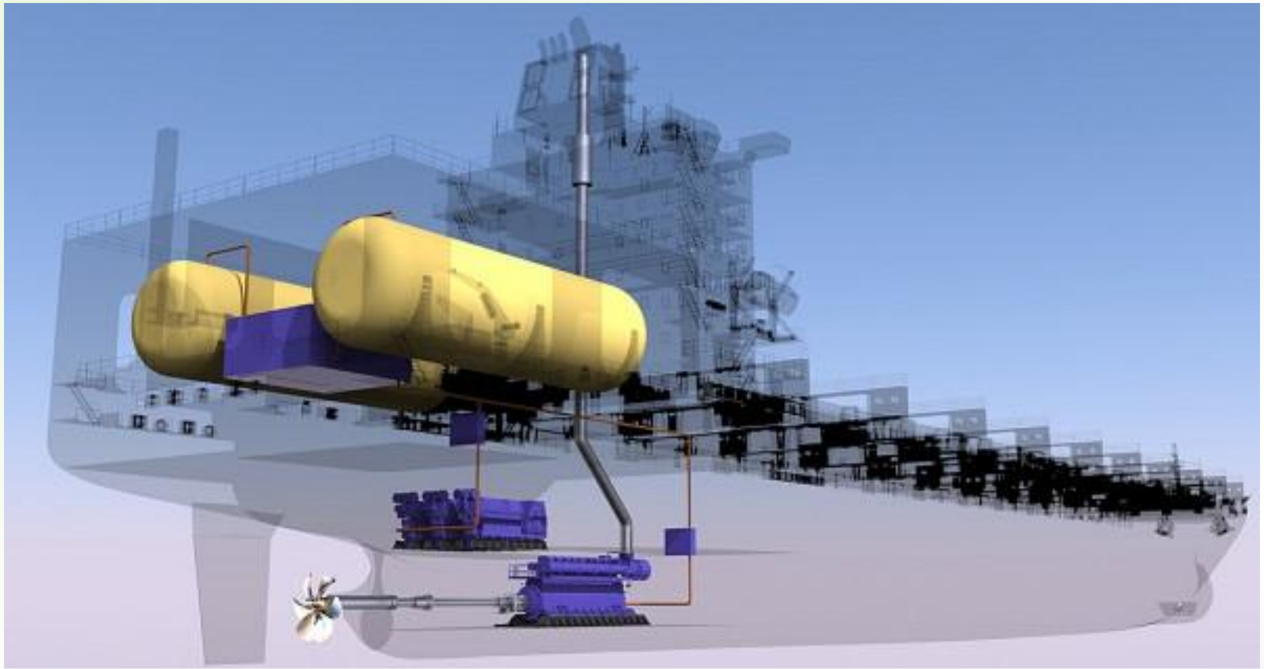
- Improving the shipping CO_2 emissions reductions.
- Increasing the vessel efficiency (fuel and energy savings).
- Reduces operational costs.

But is still important to:

- Assess the effects of mass flow rate and pinch point temperature in the WHRS size.
- Find working fluids with lower levels of flammability and toxicity.

Future work

- Improve model by adding expander and pump models.
- Equipment sizing so it will be possible to address how the mass flow rate and pinch point temperature affects the WHRS.
- Find organic fluids that can reduce hazards.



(21)

Thank you

Questions

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Institute of Marine Engineering, Science & Technology

IMAREST

CONACYT

UCL

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Results: Constant Engine Loading

Thermal efficiency at 75% MCR

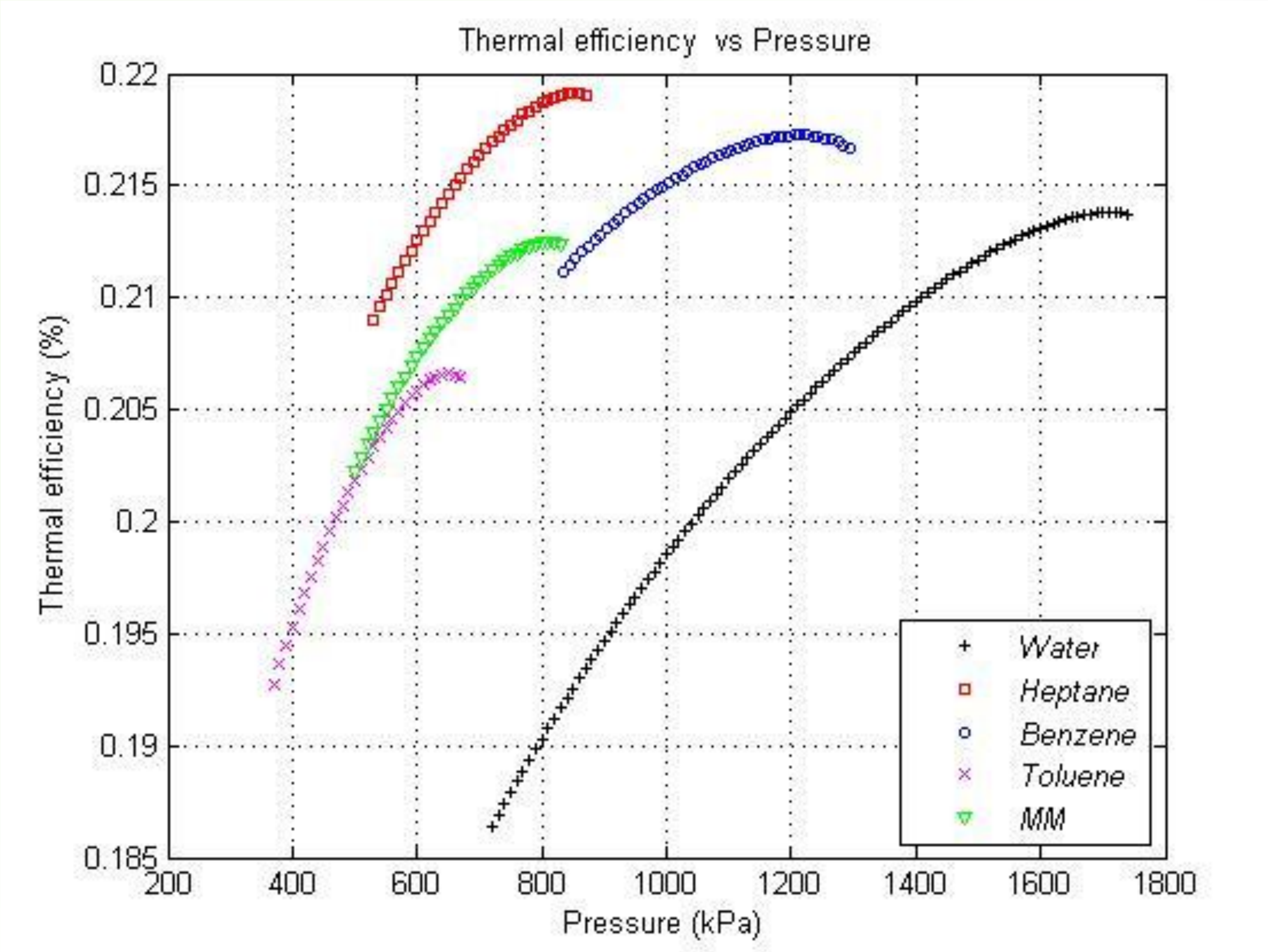
Higher

Heptane
21.9%

2.3% higher and **88.1%** more net power than RC

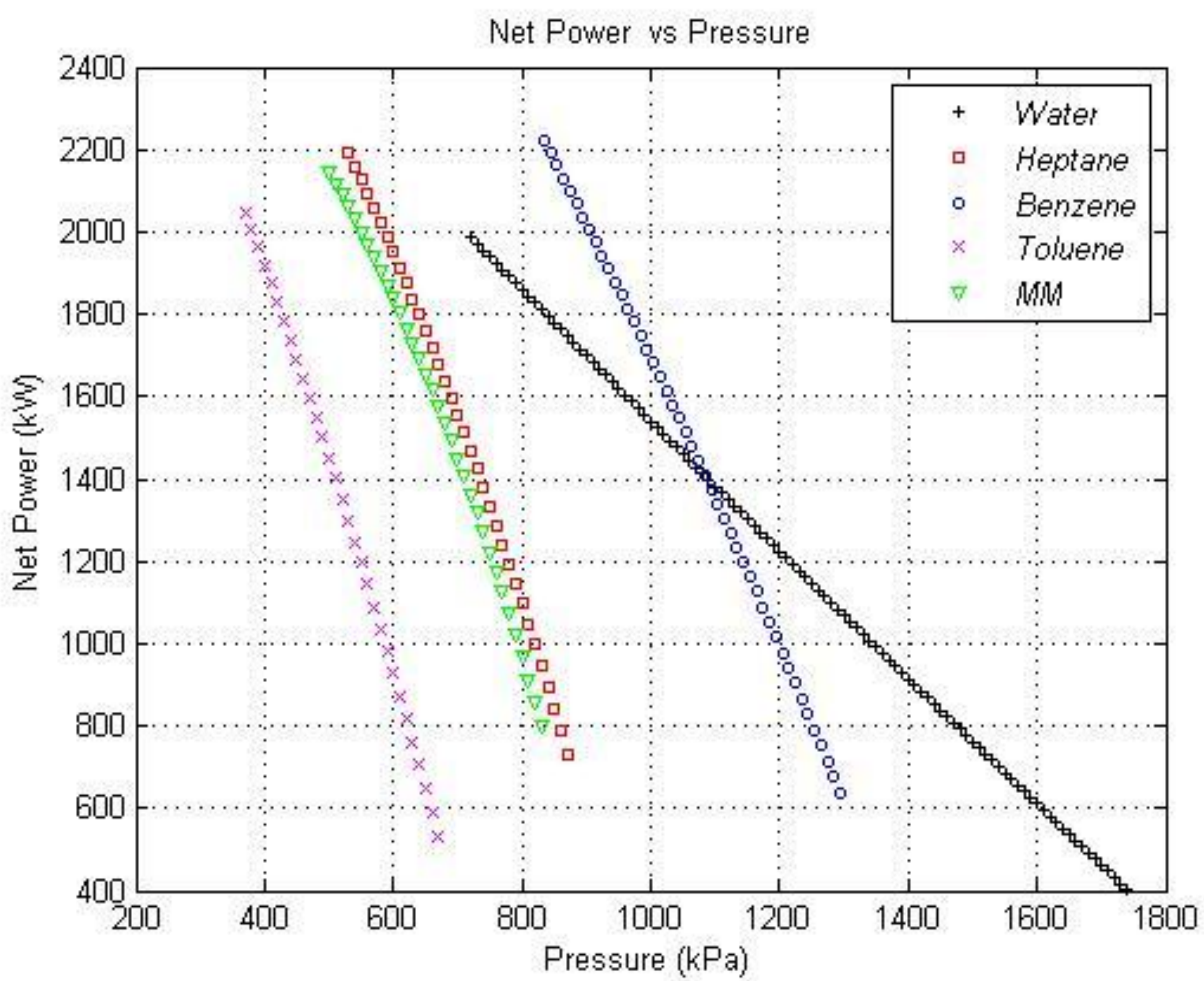
Lower

Water
21.4%



Results: Constant Engine Loading

Net Power Output at 75% MCR



<u>Higher</u>

Benzene
2,222 kW

11.8% larger

<u>Lower</u>

Water
1,987 kW

Results: Constant Engine Loading

Mass flow rate at 75% MCR

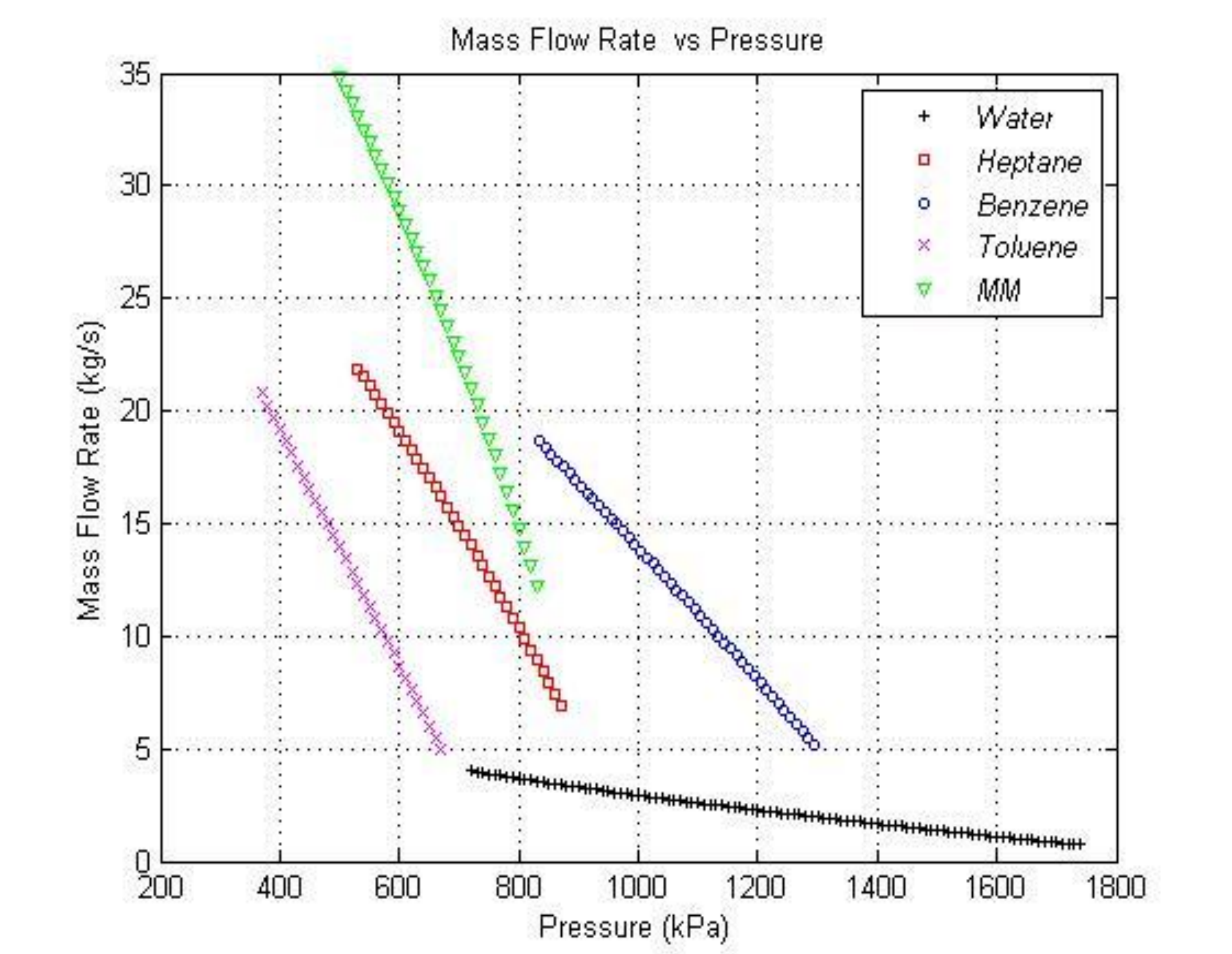
Higher

MM
34.8 kg/s

More than 700% larger

Lower

Water
4.8 kg/s



Results: Variable Engine Loading

WHRS Electrical Power returned

- Highly dependant in the heat quality.

Higher
Benzene
68.0%

A maximum difference of **15.7%** from RC

Lower
Water
57.3%